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INELASTIC SEISMIC RESPONSE OF ONE-WAY PLAN-ASYMMETRIC SYSTEMS UNDER BI-DIRECTIONAL GROUND MOTIONS

MARIO DE STEFANO, GIUSEPPE FAELLA AND ROBERTO RAMASCO*
Dipartimento di Analisi e Progettazione Strutturale, Università di Napoli Federico II, P.le Tecchio, 80125, Napoli, Italy

SUMMARY

The static design requirements of some seismic codes, such as the Eurocode 8 and—in most cases—the Uniform Building Code, to allow for the effects of earthquake excitation acting in a direction other than the principal axes of the structure do not apply to one-way asymmetric systems. Therefore, with some exceptions, no specific provisions are considered for such systems to cover effects of structural asymmetry on the behaviour of elements located along the symmetric system direction. Aimed towards fulfilling this need, in this paper, a wide parametric study of the inelastic response of one-way asymmetric systems designed according to Uniform Building Code is carried out, considering two-component earthquake excitations. The analyses show that the maximum ductility demands on elements aligned along the asymmetric system direction are very close to, and even lower than, those obtained for symmetric reference systems. Conversely, the symmetric direction elements undergo significantly larger inelasticity than if they were located in symmetric reference systems. Subsequently, the overstrength needed by the symmetric direction elements to prevent such additional ductility demands for several stiffness and plan configurations is quantified. It is concluded that one-way asymmetry should be considered by seismic codes as an intrinsic system property, thus implying that specific provisions should be included for designing elements located along the symmetric system direction, in addition to those currently subscribed to design the asymmetric direction elements.

KEY WORDS: inelastic torsional response; one-way asymmetric systems; bi-directional ground motion

INTRODUCTION

Until few years ago, most of research studies on the seismic response of plan asymmetric buildings were conducted by using uni-directional earthquake motions as input. Such an approach led to arising the controversial issues of whether or not the elements perpendicular to the seismic excitation direction should be included in the model idealization,[1,2] and, more generally, how well uni-directional analysis estimates the actual response of real buildings, which in most cases present resisting elements oriented along two orthogonal directions and, invariably, are subjected to bi-directional horizontal ground motions. In order to give an answer, researchers have started to conduct full bi-directional analyses, i.e. to study plan asymmetric systems having resisting elements along two orthogonal directions under both horizontal earthquake components. Correnza *et al.*[3] concluded that uni-directional analyses are rather suitable for all cases, except for evaluating behaviour of flexible-edge elements in short-period structures. De La Llera and Chopra,[4]

* Correspondence to: R. Ramasco, Dipartimento di Analisi e Progettazione Strutturale, Università di Napoli Federico II, Piazza le Tecchio, Napoli 80125, Italy

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using a simplified building model defined through its base shear-torque ultimate surface, related the possibility to neglect the orthogonal elements to the ground-shaking intensity.

Full bi-directional analyses have been also carried out to assess adequacy of current code torsional specifications. In a related study,[5] the consequences of the increase in accidental eccentricity, required by the present UBC 94 provisions[6] (first appeared in 1988), compared to that considered by the old ones (UBC 79), are examined. The ability of seismic codes to lead to a conservative prediction of displacements for torsionally unbalanced systems has been also verified using two-component input ground motions.[7] Bi-directional analyses have been conducted in Reference 8 to compare performance of eccentric systems designed according to the European seismic code Eurocode 8[9] with that obtained by using the UBC 94 ones. It was concluded that UBC 94 is clearly more effective than Eurocode 8 to reduce effects of torsional response in the inelastic range.

In this paper, the seismic response of a simple single-storey one-way asymmetric building model, subjected to bi-directional real earthquakes and designed according to the UBC 94 static torsional provisions, is analysed. Namely, the effect—in terms of increase in displacement ductility demands—of the system asymmetry in one direction on the response of elements located along the symmetric orthogonal direction is quantified. In other words, by focusing on response of elements acting along the symmetric system direction, this study is aimed at improving understanding on how well an effective code formulation, such as the UBC 94 one, covers torsional effects due to system asymmetry, as represented by static eccentricity. Therefore, when designing element strengths along both system directions, no allowance for accidental eccentricity has been made. The analyses show that ductility demands on elements aligned along the asymmetric system direction are very close to, and even lower than, those obtained for symmetric reference systems. Conversely, the symmetric direction elements experience significantly larger inelasticity than if they were located in the reference symmetric systems. Therefore, the overstrength needed by the latter elements to prevent such additional ductility demands is quantified for several stiffness and plan configurations. It is concluded that, in case of one-way asymmetric building, specific code provisions should be considered to design the elements located on the symmetric system direction, in addition to those currently subscribed for design of elements along the asymmetric direction. More generally, asymmetry should be considered by codes as an 'intrinsic' system property, that is to be accounted for when designing all resisting elements, independently of their alignment.

STRUCTURAL MODEL

The structural model considered in this study represents a single-storey building supported by six lateral force-resisting elements, located along the two orthogonal directions x and y, as shown in Figure 1. It is assumed that the floor diaphragm is rigid and that the resisting elements are massless.

The floor slab has plan dimensions denoted as B and L and a mass M. Two plan aspect ratios B/L are considered in the analyses, $B/L = 0{\cdot}5$ and $B/L = 1{\cdot}0$, thus covering rectangular and squared plan systems, respectively. The total mass M is assumed uniformly distributed over the floor diaphragm, so that the mass centre C_M is coincident with the geometrical floor centre and the mass radius P about C_M is equal to $\sqrt{(L^2 + B^2)/12}$.

All resisting elements are assumed to have elastic-perfectly plastic hysteretic behaviour. Each element is considered to provide stiffness and strength in its own plane only, whereas the out-of-plane stiffness and strength are assumed to be negligible. In particular, the stiffness plan distribution of the y-direction Elements 1, 2 and 3 (lateral elements) is asymmetric. Along x-direction, instead, the stiffness distribution of Elements 4, 5 and 6 (transverse or orthogonal elements) is symmetric, since stiffness of Element 4 is assumed equal to that of Element 6. Therefore, the stiffness centre C_S is located on the x-axis at a distance E_S—static or stiffness eccentricity—from the mass centre C_M.

Let k_{yi} ($i = 1,2,3$) and k_{xj} ($j = 4,5,6$) denote the elastic lateral stiffness of elements oriented along y- and x-axis, respectively, and K_x and K_y the total lateral stiffness along x- and y-axis. Then, since it is assumed

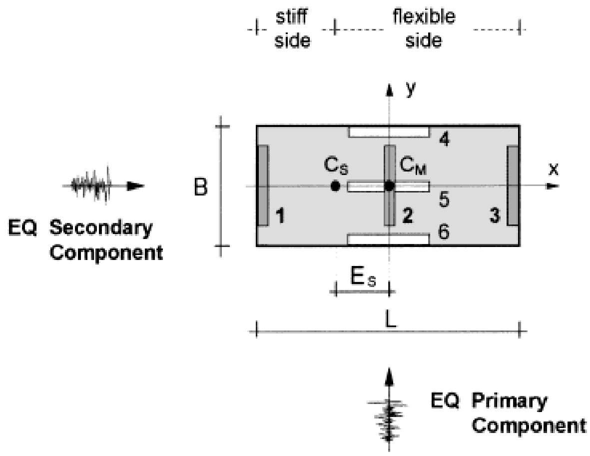

Figure 1. Idealized single storey one-way asymmetric building model

$K_x = K_y = K$, the static eccentricity E_S is given by

$$E_S = \frac{\sum_i x_i k_{yi}}{K} \tag{1}$$

while the system torsional stiffness, computed with respect to C_S, is expressed by

$$K_\Theta = \sum_i k_{yi}(x_i - E_S)^2 + \sum_j k_{xj} y_j^2 = K D_S^2 \tag{2}$$

where x_i and y_j identify the distance of the ith y-element and of the jth x-element from the mass centre and D_S represents the system stiffness radius of gyration.

It is useful to introduce the dimensionless parameters $e_S = |E_S/L|$, $d_S = D_S/L$ and $\rho = P/L$: then, the system response in the elastic range of behaviour is depending on the uncoupled translational periods $T_x = T_y = T$, the uncoupled torsional to lateral frequency ratio d_S/ρ, the normalized eccentricity e_S/ρ and the damping ratio v, taken equal to 5 per cent for both coupled modes of vibration. It has to be also noted that ρ is equal to 0·323 and to 0·408 for B/L equal to 0·5 and 1·0, respectively.

Another factor to be considered is the contribution of the elements acting along the x-direction to the system torsional stiffness, which can be represented through the parameter γ:

$$\gamma = \frac{\sum_j k_{xj} y_j^2}{K_\Theta} \tag{3}$$

Such parameter does not affect the elastic system response, but it cannot be neglected when analysing inelastic response. In real buildings, γ is certainly dependent on the plan aspect ratio B/L; therefore, γ has been set equal to 0·20 and 0·50 for B/L equal to 0·5 and 1·0, respectively. The above values characterize a two-way symmetric system having the same plan arrangement of resisting elements as the one shown in Figure 1, with all element stiffnesses k_{yi} and k_{xj} equal to $K/3$. In any case, it is demonstrated later that even a strong variation in this parameter is not affecting significantly the response quantities of interest in this paper.

Once the above-defined parameters $T_x = T_y = T$, d_S/ρ, e_S/ρ and γ are fixed, all element stiffnesses are uniquely determined.

INPUT GROUND MOTIONS

An ensemble of five pairs of horizontal components of real earthquakes has been used as input ground motion for the inelastic response analysis of the building model. The main characteristics of the selected records are reported in Table I. For each pair of records, the component having the higher peak ground acceleration (PGA) has been arbitrarily assumed to act along the system asymmetric y-direction. The other component has been taken as x-direction input. No investigation has been developed to explore the effect of variation in the incidence angle of the input ground motion. As it will be shown in the next section, for each of the two system directions, the design lateral force has been evaluated with the constant ductility inelastic spectra of the relevant earthquake component, in order to minimize the effects of the above arbitrary assumption.

For the x- and the y-direction components, Figure 2 shows the mean 5 per cent damped amplification spectra (denoted as β), that is the elastic acceleration response spectra normalized to PGA, along with the amplification spectrum proposed by UBC 94 for soil Type 2. It can be seen that, on average, the considered ensemble of ground motions can adequately represent the seismic excitation adopted by UBC 94 for deep cohesionless or stiff clay soils.

DESIGN OF ELEMENT STRENGTHS

When designing the element strengths, the first step requires the definition of the design lateral forces F_x and F_y for the x- and the y-direction, respectively. To compute F_x and F_y, for each pair of earthquake records, the

Table I. Earthquake records used as input ground motion

Earthquake	Date	Station	Duration (sec)	Primary component PGA (g)	Secondary component PGA (g)
Imperial Valley	18.05.40	El Centro	53·40	0·348	0·214
Kern County	21.07.52	Taft	54·40	0·179	0·156
Montenegro	15.04.79	Petrovac	19·60	0·438	0·305
Valparaiso	03.03.85	El Almendral	72·02	0·284	0·159
Northridge	17.01.94	Newhall	59·98	0·590	0·583

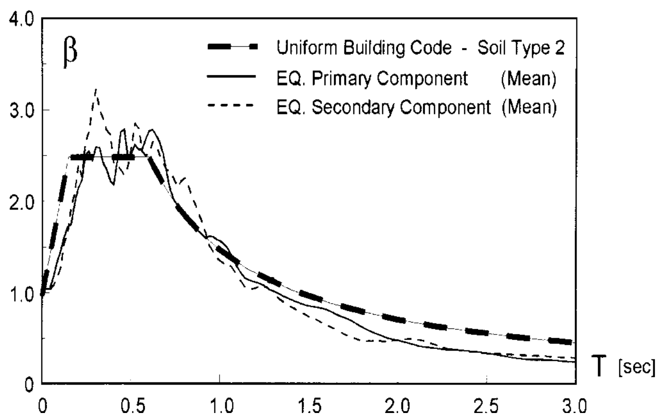

Figure 2. Mean normalized elastic spectra of selected earthquake records

inelastic acceleration spectra S_{ax} and S_{ay} have been computed for an imposed displacement ductility demand equal to 4. Therefore, the design lateral forces have been obtained through the following equations:

$$F_x = MS_{ax}(T) \tag{4a}$$

$$F_y = MS_{ay}(T) \tag{4b}$$

The lateral forces F_x and F_y represent the strength needed by a 5 per cent damped single-degree-of-freedom (SDOF) system—taken as symmetric reference system—having a period T equal to the uncoupled period of the asymmetric system to be designed when the imposed maximum ductility demand, both under the x- and under the y-direction record, is equal to 4. As a consequence, if there was no asymmetry ($e_S = 0$), the resisting elements of the analysed model would experience a ductility demand of 4, independent of the uncoupled period T and, of course, of the input earthquake. Then, all elements are expected to be well excited into the inelastic range when the system is subjected to the selected earthquakes. It has been chosen to re-design the system for each of the five pairs of input records, instead of designing it only once with the mean inelastic spectra of the x- and the y-direction components, since it is believed that the mismatch in spectral ordinates between the input ground motion and the mean spectra may lead to inconsistent results.

The UBC 94 static torsional provisions have been adopted for distributing strength among the lateral y-direction elements. Since the aim of this paper is to evaluate how well UBC 94 regulations account for effects of the structural asymmetry when systems are subjected to bi-directional ground motions, the term allowing for accidental eccentricity (0·05L) has been subtracted from the UBC formulas for design eccentricity (see equations (5) below). In other words, since torsional provisions basically consist of applying the system lateral forces with a design eccentricity, in this study the so-called dynamic eccentricity will be considered only, thus neglecting the accidental eccentricity term. Furthermore, when designing resisting elements along both x- and y-directions, the UBC requirement that allows for effects of earthquake forces acting in a direction other than the principal axes (Section 1631.1) has not been considered since it does not apply to most one-way asymmetric systems (no plan irregularity Type A as given in Table 16-M for *both* major axes). For one-way asymmetric systems, such requirement is to be observed only if 'non-parallel' lateral load-resisting systems are present and/or a column forms part of two or more intersecting lateral load-resisting systems, provided that the axial load in the column due to seismic forces is larger than 20 per cent of the column allowable axial load. Thus, for a wide class of one-way asymmetric buildings, i.e. when resistance to lateral loads is provided either by shear walls or by 3D frames (unless the aforementioned circumstance relative to columns applies), no specific requirement for orthogonal effects is to be complied with. As a consequence, in this paper design has been conducted with seismic forces acting non-concurrently along x- and y-directions.

The design of the y-direction Elements 1, 2 and 3 is conducted by applying the lateral force F_y at a distance e_d (design eccentricity normalized to plan dimension L) from the stiffness centre C_S. If the non-dimensionalized accidental eccentricity term, i.e. 0·05, is neglected, the application of the UBC 94 provisions leads to the following equations for the design eccentricity e_d:

$$e_d^+ = e_S + 0{\cdot}05(A_x - 1) \tag{5a}$$

$$e_d^- = e_S - 0{\cdot}05(A_x - 1) \tag{5b}$$

where A_x is an amplification factor of the accidental eccentricity, which accounts both for torsional flexibility of the building and for static eccentricity. Equations (5) are obtained from the well-known expressions subscribed by UBC 94, by subtracting the non-dimensional accidental eccentricity term (0·05). According to the code, the values of A_x, given by

$$A_x = \left[\frac{w_{max}}{1{\cdot}2 w_{avg}}\right]^2 \tag{6}$$

where w_{max} and w_{avg} are the maximum and the average diaphragm horizontal displacements of the model, respectively, have to be included between 1 and 3.

The design element strength F_{yi} has been computed using either equations (5a) or (5b), whichever results in the higher absolute value, according to the following equation:

$$F_{yi} = \frac{k_{yi}}{K} F_y \left[1 + \frac{e_d}{d_S^2} \frac{x_i}{L} \right] \tag{7}$$

Furthermore, the so-called no negative shear requirement has been applied when designing the stiff side Element 1.

Since the larger element strength provided by the two design eccentricities is to be considered, code-designed systems present a total strength along the y-direction which is greater than the design lateral force F_y. Such increment in strength can be expressed through an overstrength factor $O_{fy} = \sum_i F_{yi}/F_y$. As it is well known, the overstrength O_{fy} increases with the stiffness eccentricity e_S and, conversely, diminishes as the system torsional stiffness amplifies. Furthermore, O_{fy} reduces significantly as B/L varies from 0·5 to 1·0.[8]

In order to be consistent with the assumption of neglecting accidental eccentricity, for the symmetric x-direction elements, the design force F_x has been distributed in proportion to their stiffness and no overstrength, resulting from the application of 'accidental' torsional moments (as recommended by the considered seismic code), is given to the perimeter Elements 4 and 6. Therefore, the element yield force F_{xj} is provided by the well-known formula

$$F_{xj} = \frac{k_{xj}}{K} F_x \tag{8}$$

PARAMETRIC STUDY

An extensive parametric analysis has been conducted in order to achieve more general conclusions. Namely, the system uncoupled period T along both x- and y-direction has been varied between 0·1 and 1·5 sec. As far as the uncoupled frequencies ratio d_S/ρ is concerned, three values have been selected ($d_S/\rho = 0{\cdot}80$, 1·00 and 1·20) to cover both torsionally flexible ($d_S/\rho < 1{\cdot}0$) and torsionally stiff ($d_S/\rho > 1{\cdot}0$) systems. It should be noted that the parameter d_S/ρ is able to characterize the system tendency to undergo torsional response since it has been assumed that $T_x = T_y = T$. However, it is believed that definition of whether or not a system should be classified as torsionally flexible (or torsionally stiff) deserves further investigation if T_x is different from T_y.

For the non-dimensional stiffness eccentricity two values have been chosen: $e_S = 0{\cdot}10$ and 0·20, in order to cover systems having moderate to large eccentricity. When comparing behaviour of rectangular and squared floor systems having different mass radius ρ, reference has been also made to parameter e_S, rather than to the normalised eccentricity e_S/ρ, since the former is believed to be more significant for the engineering practice. In any case, the above two values of e_S correspond to $e_S/\rho = 0{\cdot}3096$ and 0·6192 for the rectangular model and to $e_S/\rho = 0{\cdot}2451$ and 0·4902 for the squared model.

The well-known displacement ductility demand has been selected as damage parameter; in particular, such parameter has been evaluated for each resisting element (denoted as μ_{xj} and μ_{yi} for x- and y-direction elements, respectively) and the mean values $\bar{\mu}_{xj}$ and $\bar{\mu}_{yi}$ over the five considered earthquakes have been computed, as the system parameters vary within the above-mentioned ranges. Furthermore, for both x- and y-directions, the mean values over the five earthquakes of the maximum ductility demands—$\bar{\mu}_{x,\max}$ and $\bar{\mu}_{y,\max}$, respectively—among the three relevant elements have been adopted as reference parameter for comparing the performances of the x- and the y-direction elements of the asymmetric systems under investigation with their reference symmetric counterparts.

DUCTILITY DEMAND ON y- AND x-DIRECTION ELEMENTS

The investigation has been initially aimed at assessing the inelastic response along both principal directions x and y of UBC-designed systems. Figure 3(a) reports the mean ductility demands of the three y-direction elements of rectangular plan systems ($B/L = 0{\cdot}5$) having $d_S/\rho = 1{\cdot}00$ and $e_S = 0{\cdot}10$. It can be seen that, except for the very short period range, values of $\bar{\mu}_{yi}$ ($i = 1,2,3$) are included in a rather narrow band, leading to the conclusion that UBC 94—even when modified according to equations (5)—is successful in achieving an almost uniform distribution of damage among elements located along the system asymmetric direction. Furthermore, if one looks at the mean values of the maximum ductility demands $\bar{\mu}_{y,\max}$ among the y-elements, it emerges clearly that such values are very close to, and many cases even lower than, the value of 4, which characterizes the response of the symmetric counterparts. This trend evidences that the part of UBC 94 torsional provisions accounting for effects of the system asymmetry, as represented by the static eccentricity e_S, is very effective, being those effects practically eliminated. This achievement is confirmed also for squared plan systems ($B/L = 1{\cdot}0$), as shown in Figure 4(a) and for different sets of system parameters. Going more into detail, for both aspect ratios, curves of $\bar{\mu}_{yi}$ indicate that, on average, the flexible side Element 3 presents the largest ductility demand for short period systems, while the stiff side Element 1 becomes the most critical as the system uncoupled period elongates. UBC 94 systems achieve such good performance along the asymmetric y-direction with an overstrength O_{fy} equal to 1·16 and 1·08 for $B/L = 0{\cdot}5$ and 1·0, respectively.

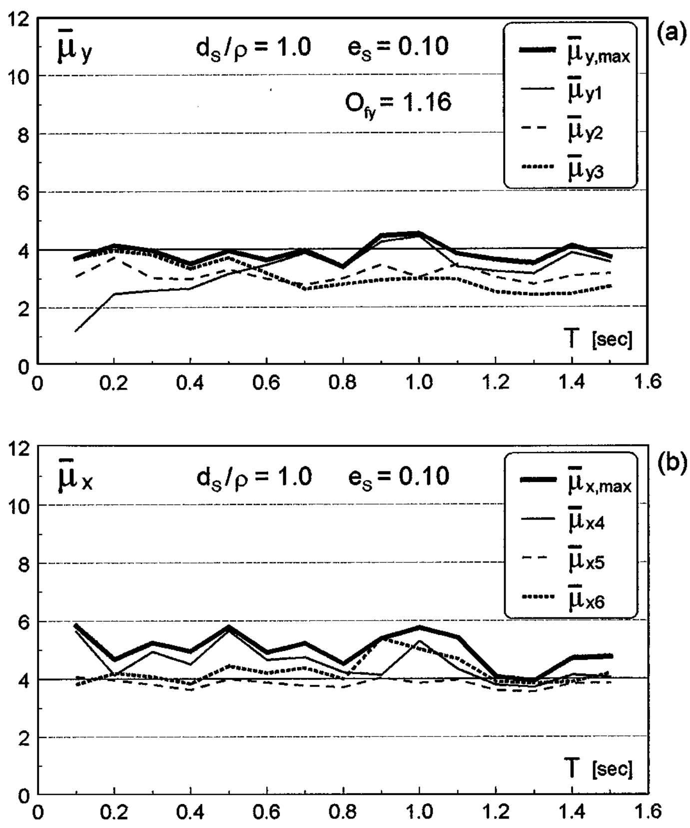

Figure 3. Mean ductility demands on elements of rectangular plan systems ($B/L = 0{\cdot}5$)

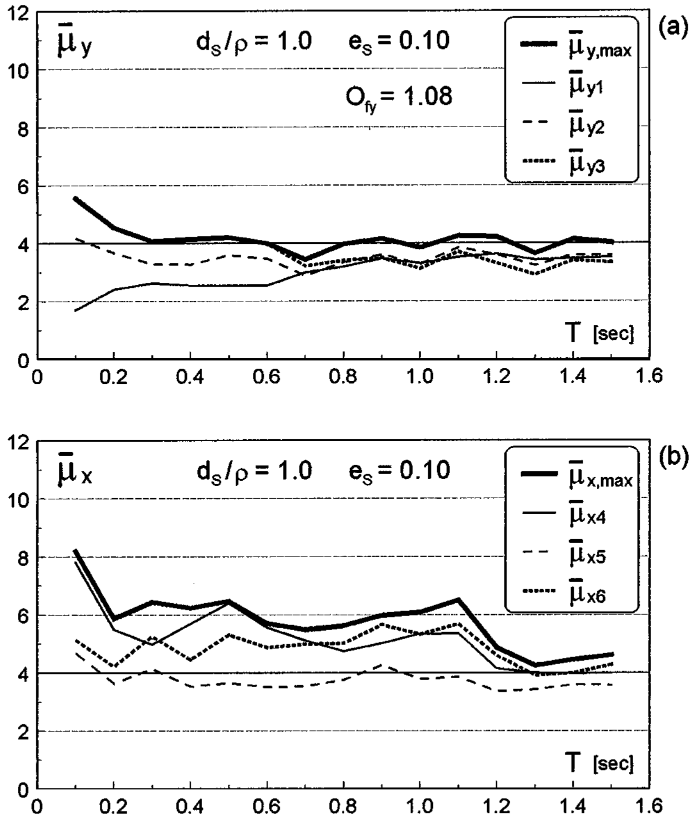

Figure 4. Mean ductility demands on elements of squared plan systems ($B/L = 1{\cdot}0$)

As expected, due to lack of overstrength along the symmetric direction, x-elements experience larger ductility demands than if they were located in a symmetric system, the values of $\bar{\mu}_{x,\max}$ being larger than 4 both for $B/L = 0{\cdot}5$ and for $B/L = 1{\cdot}0$ (Figures 3(b) and 4(b), respectively). Obviously, the perimeter Elements 4 and 6, in turn, experience the largest ductility demands. It can be also observed that x-elements of squared plan systems are subjected to higher ductility demands than their rectangular plan counterparts.

Therefore, as the aspect ratio increases towards the unity, the effect of eccentricity about the y-axis on the inelastic response of resisting elements located along the system symmetric direction amplifies. This is primarily due to the fact that floor rotations induce larger increase in x-displacements when the plan dimension B enlarges. Furthermore, as previously noted, the code provides rectangular plan systems with larger overstrength O_{fy} along the asymmetric y-direction than their squared plan counterparts: this leads to slightly lower plastic demands also in the orthogonal symmetric direction.

OVERSTRENGTH NEEDED BY THE SYMMETRIC DIRECTION ELEMENTS

The above-described results have shown that, for one-way asymmetric structures under bi-directional input ground motions, the considered torsional specifications, as well as others,[8] are inadequate to prevent effects of system eccentricity in a direction other than the asymmetric one.[10] Therefore, in this section an attempt to cover, for the systems under investigation, the effects of asymmetry also for x-elements is accomplished.

Namely, keeping design of y-direction elements as fixed, it has been searched for the increase in total strength needed by the x-elements to reduce the value of their maximum ductility demands to 4 which characterizes the response if there is no eccentricity. Two ways to distribute the overstrength O_{fx} along x-direction have been explored: according to the first one, O_{fx} is distributed among the three Elements 4, 5 and 6 in proportion to their stiffness (Criterion 1); according to the second one, only the perimeter Elements 4 and 6 are provided with O_{fx} (Criterion 2). The latter procedure has been investigated since, at a first glance, it appears more efficient than the former due to the fact that Elements 4 and 6 present always larger ductility demands than Element 5, as shown previously. As a matter of fact, an approach similar to that of Criterion 2 is subscribed by Eurocode 8 for a simplified analysis of effects of accidental eccentricity in case of symmetric distribution of lateral stiffness and mass.

The above two methodologies have been calibrated to systems whose y-direction elements are designed according to UBC 94, since its torsional recommendations, as confirmed earlier, are widely recognized as very effective. In other words, this attempt to improve the response of the x-direction elements has been conducted with reference to one of the codes which has been proved to be most effective along the asymmetric y-direction.

Regarding the first criterion to distribute overstrength, values of O_{fx} have been determined for the whole range of selected system parameters and for the five bi-directional earthquake excitations. The influence of torsional stiffness, as expressed by the ratio d_S/ρ, emerges from Figure 5, which reports the computed values of O_{fx} (represented by solid circles) for rectangular plan systems having $e_S = 0{\cdot}10$, as d_S/ρ ranges between 0·8 and 1·2. It can be seen that O_{fx} is affected by torsional stiffness to a large extent since it reduces significantly with increase in d_S/ρ. Furthermore, the needed overstrength grows with increase in stiffness eccentricity, as indicated by comparison of Figure 6, where O_{fx} is plotted for rectangular systems with $d_S/\rho = 1{\cdot}0$ and $e_S = 0{\cdot}20$, with Figure 5b. Therefore, the trend of O_{fx} with d_S/ρ and e_S is similar to that of the overstrength O_{fy} provided by the code along the asymmetric system direction. However, the computed values of O_{fx} present an opposite trend compared to the code O_{fy} when sensitivity to the plan aspect ratio is examined. This behaviour emerges from comparison of Figure 7, which refers to systems with $B/L = 1{\cdot}0$, with Figure 5b: as B/L increases, O_{fx} increases whereas O_{fy} does not.

Generally, values of O_{fx} are remarkably affected by the input ground motion; in most cases, they do not exceed 1·5, but for torsionally flexible squared plan systems some peaks are even larger than 2·0. However, to derive useful indications for design, it is worth referring to mean values of the overstrength. In analogy with the code approach for the asymmetric y-direction, which leads to overstrengths O_{fy} independent of the uncoupled period T, values of O_{fx} have been averaged not only with respect to the five selected earthquakes but also with respect to T. Each of Figures 5–7 reports a solid line corresponding to the above-defined mean values $\bar{O}_{fx}$, while the two dashed lines refer to the mean plus and minus one standard deviation. It can be observed, then, that the band included between the dashed lines, which measures the scatter of O_{fx} with respect to its mean $\bar{O}_{fx}$, becomes narrower as torsional stiffness increases and stiffness eccentricity decreases.

Table II summarizes, for all considered values of d_S/ρ, e_S and B/L, the computed means $\bar{O}_{fx}$, which confirm the trends, previously discussed with reference to O_{fx}, with system parameters.

In most cases, for the selected parameters d_S/ρ, e_S and B/L, the means $\bar{O}_{fx}$ are very close to, and in some cases larger than, their code counterparts O_{fy} applied to the system y-direction.

For rectangular plan systems, the need for such significant increase in strength along the symmetric x-direction is basically due to the fact that, according to this first criterion, $\bar{O}_{fx}$ is distributed among x-elements in proportion to their stiffness. As a result, this criterion appears not very efficient, since a large part of overstrength is provided to Element 5, which undergoes lesser inelasticity than the perimeter elements. For squared plan systems, in addition to the above reason, the high values of $\bar{O}_{fx}$ are due to lower overstrength along the y-direction.

Then, the second criterion to apply overstrength along the x-direction is worth exploring, which consists of increasing strength of the perimeter Elements 4 and 6 only. Let O^{I}_{fx} denote the overstrength factor applied to

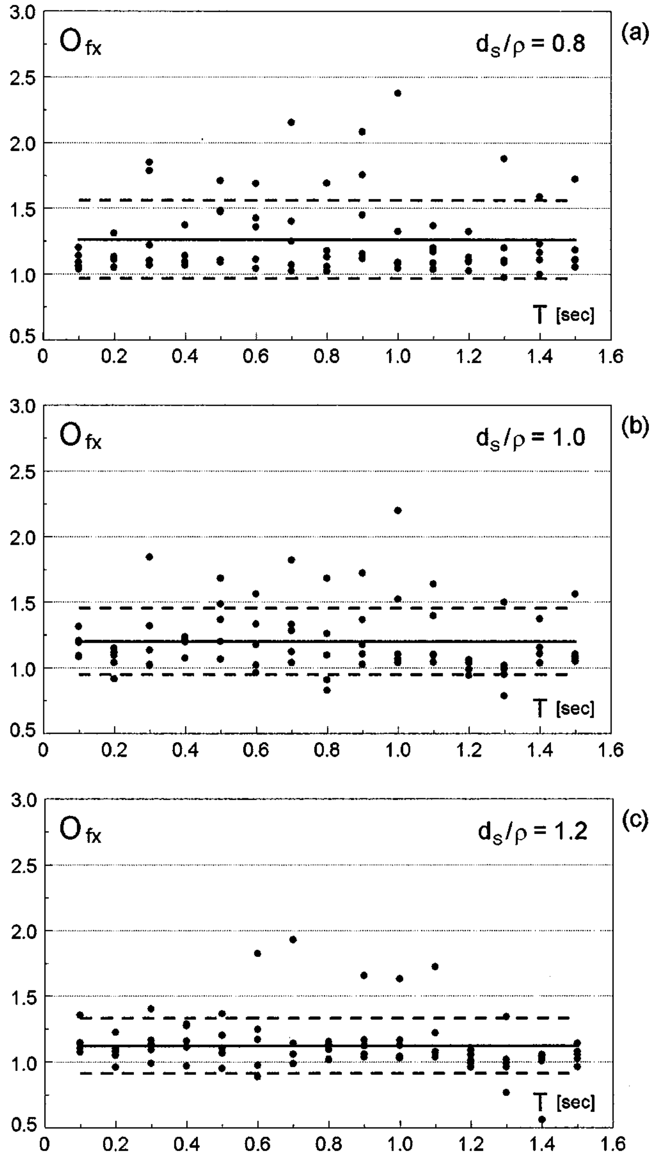

Figure 5. Computed overstrength for x-direction elements of rectangular systems having $e_S = 0{\cdot}10$

both Elements 4 and 6. Then, the global factor O_{fx} is given by:

$$O_{fx} = O^{\mathrm{I}}_{fx}\frac{k_{x4}}{K} + \frac{k_{x5}}{K} + O^{\mathrm{I}}_{fx}\frac{k_{x6}}{K} \tag{9}$$

For the five considered pairs of earthquake records, Figure 8 shows curves of O_{fx} obtained with the second criterion for a rectangular plan system having $d_S/\rho = 1{\cdot}0$ and $e_S = 0{\cdot}10$. It can be seen that in most cases the needed overstrength is clearly lower than that corresponding to the first criterion. However, for one case relative to the Petrovac excitation, it has not been possible to define O_{fx}, since the ductility demand of

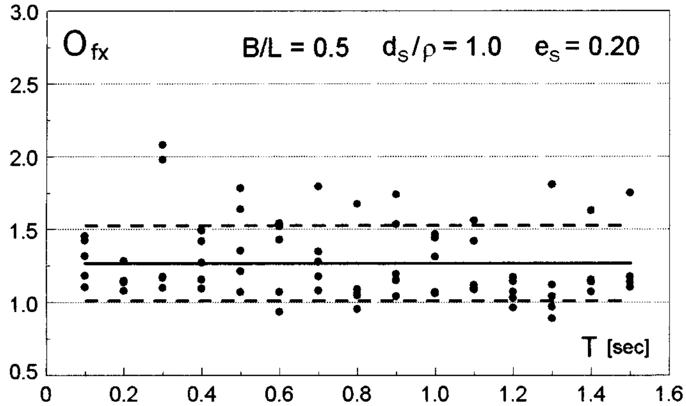

Figure 6. Computed overstrength for x-direction elements of rectangular systems having $d_S/\rho = 1{\cdot}0$ and $e_S = 0{\cdot}20$

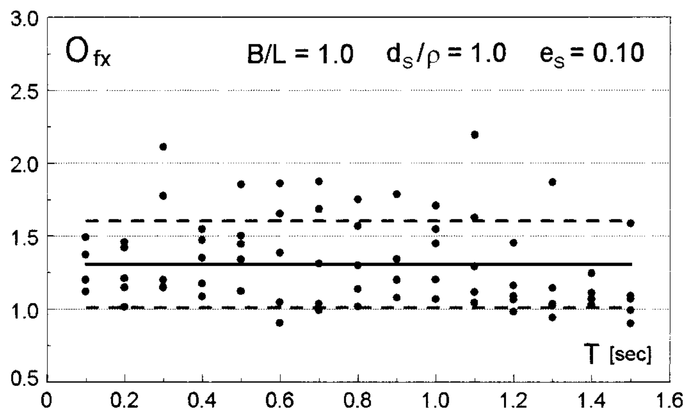

Figure 7. Computed overstrength for x-direction elements of squared systems having $d_S/\rho = 1{\cdot}0$ and $e_S = 0{\cdot}10$

Table II. Criterion 1: mean values $\bar{O}_{fx}$ of the needed overstrength

B/L	d_S/ρ	e_S	$\bar{O}_{fx}$
	0·80	0·10	1·26
	1·00	0·10	1·20
0·5	1·20	0·10	1·12
	1·00	0·20	1·27
	1·20	0·20	1·18
	0·80	0·10	1·42
1·0	1·00	0·10	1·31
	1·20	0·10	1·23

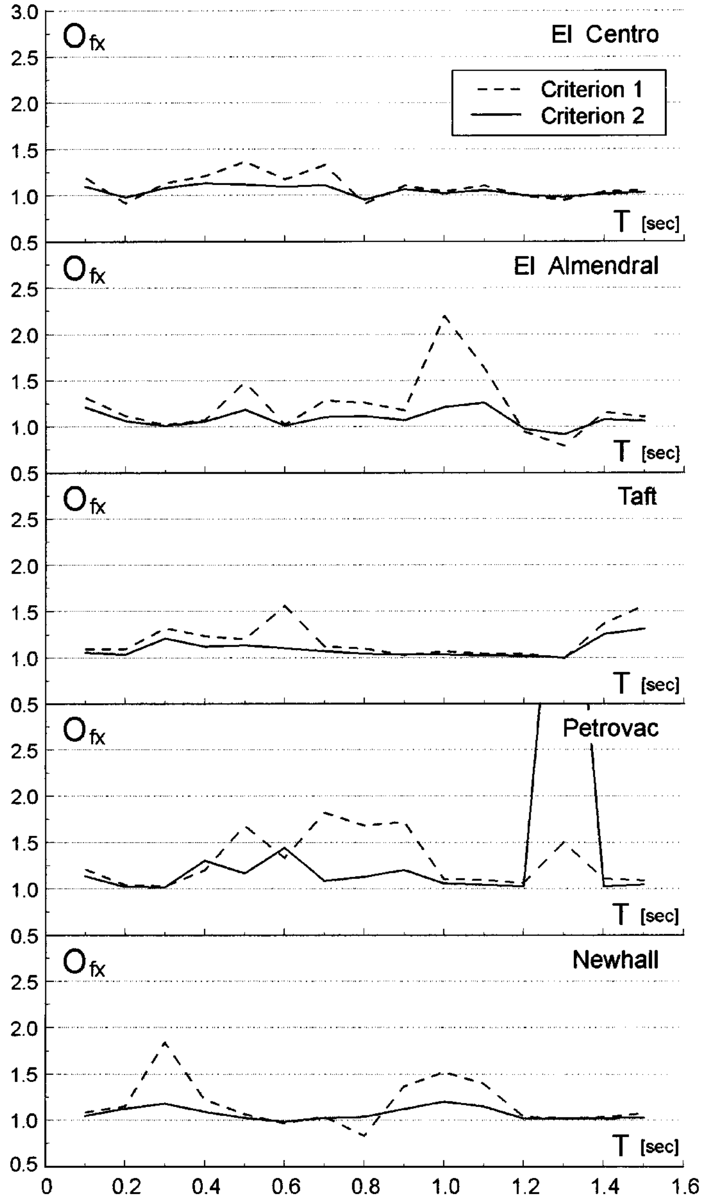

Figure 8. Rectangular systems having $d_S/\rho = 1{\cdot}0$ and $e_S = 0{\cdot}10$: comparison between the x-direction overstrengths relative to the two considered criteria

Element 5 was always greater than 4, independently of the overstrength given to Elements 4 and 6. If the mean $\bar{O}_{fx}$ is determined over the computed values of the overstrength O_{fx}, its value drops to 1·08 with a remarkable reduction with respect to the overstrength ($\bar{O}_{fx} = 1{\cdot}20$) needed with the first criterion. For larger stiffness eccentricity, it has been found that the second criterion fails more times, thus implying that its improved efficiency, compared to the first criterion, is partially counterbalanced by an inferior reliability.

A final analysis has been carried out in order to assess the influence of the parameter γ, i.e. the assumed contribution of the x-elements to the total torsional stiffness, on values of the needed overstrength O_{fx}. In

particular, O_{fx} has been evaluated for a rectangular plan system, having $d_S/\rho = 1{\cdot}00$ and $e_S = 0{\cdot}10$, when γ is equal to 0·50 (instead of 0·20). The variation in O_{fx} for such large increase in γ is very modest: In most cases, a slight reduction in O_{fx} is found, which results in the mean $\bar{O}_{fx}$ to decrease from 1·20 (Table II) to 1·16. Therefore, no significant deviations from values reported in Table II should be expected as γ varies within broad ranges.

CONCLUSIONS

In this paper, the seismic response under two-component ground motions of one-way asymmetric systems designed according to Uniform Building Code has been evaluated. In particular, the analysis has focused on how well such regulations, which are widely recognized as very effective, account for the structural asymmetry, as represented by stiffness eccentricity, thus neglecting the issue of accidental eccentricity. It has been shown that UBC static torsional provisions success to prevent effects of torsional response for elements located along the system asymmetric direction. In particular, along such direction, UBC design results in almost uniform plan distribution of inelastic actions, with maximum ductility demands among resisting elements very close or even smaller than the value characterizing the response of equivalent symmetric systems. However, along the symmetric system direction, this code appears inadequate to protect the corresponding resisting elements, since no allowance is made for effects induced by floor rotations. It has been seen that, on average, the maximum ductility demands among the symmetric direction elements practically always exceed their symmetric counterpart. In order to overcome this shortcoming, an overstrength, which the symmetric system direction should be provided with, has been evaluated.

Two ways to apply such overstrength have been explored. In both cases, it has been found that such increase in strength is dependent on the plan aspect ratio, in addition to the elastic system parameters. If overstrength is given to all symmetric direction elements in proportion to their stiffness, its values are in many cases close or even larger than those applied by UBC to design the asymmetric direction elements. This result is due to the fact that overstrength is not spent effectively. If overstrength is given, instead, to the perimeter symmetric direction elements only, its values drop significantly. However, in a few number of cases, when the inner symmetric direction element ends up with experiencing the largest inelasticity, this latter criterion fails to reduce ductility demands up to the value of the symmetric reference system.

Then, it can be concluded that asymmetry should be considered by codes as an intrinsic system property. As a result, one-way asymmetric buildings should be *always* designed with special provisions accounting for torsion due to structural asymmetry also in their symmetric direction.

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